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IMPROVED METHOD FOR PROJECTION PRINTING USING A MICROMIRROR SLM

Field of the invention:

The present invention relates to the printing of patterns with extremely high precision on photosensitive surfaces, such as photomasks for semiconductor devices and displays. It also relates to direct writing of semiconductor device patterns, display panels, integrated optical devices and electronic interconnect structures. Furthermore, it can have applications to other types of precision printing such as security printing. The term printing should be understood in a broad sense, meaning exposure of photoresist and photographic emulsion, but also the action of light on other light sensitive media such as dry-process paper, by ablation or chemical processes activated by light or heat. Light is not limited to mean visible light, but a wide range of wavelengths from infrared to extreme UV. Of special importance is the ultraviolet range from 370 nm (UV) through deep ultraviolet (DUV), vacuum ultraviolet (VUV) and extreme ultraviolet (EUV) down to a few nanometers wavelength.

In a different sense the invention relates to the art and science of spatial light modulators and projection displays and printers using such modulators. In particular it improves the grey-scale properties, the image stability through focus and image uniformity and the data processing for such modulators by application of analog modulation technique. The most important use of the analog modulation is to generate an image in a high-contrast material such as photoresist with an address grid, i.e. the increment by which the position of an edge in the pattern is specified, that is much finer than the grid created by the pixels of the spatial light modulator.

Background

It is known in the current art to build precision pattern generators using projection of micromirror spatial light modulators (SLMs) of the micromirror type (Nelson 1988, Kück 1990). To use an SLM in a pattern generator has a number of advantages compared to the more wide-spread method of using scanning laser spots: the SLM is a massively parallel device and the number of pixels that can be written per second is extremely high. The optical system is also simpler in the sense that the illumination of the SLM is non-critical, while in a laser scanner the entire beam path has to be built with high precision. Compared to some types of scanners, in particular electrooptic and acoustooptic ones, the micromirror SLM can be used at shorter wavelengths since it is a purely reflective device.

In both references cited above the spatial modulator uses only on-off modulation at each pixel. The input data is converted to a pixel map with one bit depth, i.e. with the values 0 and 1 in each pixel. The conversion can be done effectively using graphic processors or custom logic with area fill instructions.

In a previous application by the same inventor Sandström (Sandström et. al. 1990). the ability to use an intermediate exposure value at the boundary of a pattern element to fine-adjust the position of the element's edge in the image created by a laser scanner was described.

It is also known in the art to create a grey-scale image, preferably for projection display of video images and for printing, with an SLM by variation of the time a pixel is turned on or by printing the same pixel several times with the pixel turned on a varying number of times.
The present invention devices a system for direct grey-scale generation with a spatial light modulator, with a special view to the generation of ultra-precision patterns. Important aspects in the preferred embodiments, are uniformity of the image from pixel to pixel and independence of exact placement of a feature relative to the pixels of the SLM and stability when focus is changed, either with intention or inadvertently.

Brief descriptions of the drawings
Figure 1 shows a printer in prior art. The SLM consists of micromirrors that deflect the light from the lens pupil.

Figure 2 shows a number of pixel designs with the uppe four pixels in an off state and the remaining five pixels turned on.

Figure 3 shows an array of pixels moving up and down like pistons, thereby creating a phase difference. The figure shows how the pixels are controlled to create the reflectivity in the inset. The bright areas have pixels with 0 phase, while dark areas are created by pixels with alternating +90 and -90 degree phase. The oblique boundaries between bright and dark areas are created by intemediate values of phase. This is how an edge can be fine-positioned with a phase-type SLM.

Explanation of the invention.

The basis for understanding the invention is the generic arrangement in Figure 1 which shows a generic projection printer with an SLM. Spatial light modulators based on reflection come in two varieties, the deflection type (Nelson) and the phase type (Kück). The difference between them may in a particular case with micromirrors seem small, but the phase SLM extinguishes the beam in the specular direction by destructive interference, while a pixel in a deflection SLM deflects the specular beam geometrically to one side so that it misses the aperture of the imaging lens as shown in figure 1. For ultra-precise printing as performed in the current invention the phase-modulating system as described by Kück 1990 is superior to the deflecting type. First, it has better contrast since all parts of the surface, also hinges and support posts, take part in the destructive interference and total extinction can be achieved. Second, a system that works by deflecting the light to the side is difficult to make symmetrical around the optical axis

at intermediate deflection angles, creating a risk of feature instability when focus is changed. In the preferred embodiments the phase type is used, but if one accepts or designs around the asymmetry of the deflection type it could also be used.

The phase SLM can be built either with micromachined mirrors, so called micromirrors, or with a continuous mirror surface on a supporting substrate that is possible to deform using an electronic signal. In Kück 1990 a viscoelastic layer controlled by an electrostatic field is used, but it is equally possible, especially for very short wavelengths where deformations of the order of a few nanometer are sufficient, to use a piezoelectric solid disk that is deformed by electric field or another electrically, magnetically or thermally controlled reflecting surface. For the remainder of this application an electrostatically controlled micromirror matrix (one- or two-dimensional) is assumed, although other arrangements as described above are possible.

The invention uses a micromirror where the phase modulation is variable to obtain a variable amount of light reaching the pupil of the projection lens. Figure 2 shows some multi-element mirrors. The tilts of the various parts of the mirrors are unimportant. In fact one element by itself would direct the light toward the lens while another would direct it outside of the pupil. The correct way to understand the function is to look at the complex amplitude reaching the center of the pupil from each infinitesimal area element of the mirror and integrate the amplitude over the mirror. With a suitable shape of the mirror it is possible to find a deformation where the complex amplitudes add up to almost zero, corresponding to no light reaching the pupil. This is the off-state of the micromirror, while a relaxed

state where the mirror surface is flat and the complex amplitudes add in phase is the on-state. Between the on and off-states the amount of light in the specular direction is a continuous but non-linear function of the deformation.

The pattern to be written is normally a binary pattern, such as a photomask pattern in chrome on a glass substrate. In this context binary means that there are no intermediate areas: a certain point on the photomask surface is either dark (covered with chrome) or clear (no chrome). The pattern is exposed in photoresist by the projected image from the SLM and the photoresist is developed. Modern resists have high contrast, meaning that a small percentage change in exposure makes the difference between full removal of the resist in the developer and hardly any removal at all. Therefore the photoresist has an edge that is normally almost perpendicular to the substrate surface, even though the aerial image has a gradual transition between light and dark. The chrome etching does further increase the contrast, so that the resulting image is perfectly binary: either opaque or clear with no intermediate areas.

The input data is in a digital format describing the geometry of the pattern to be written on the surface. The input data is often given in a very small address unit, e.g. 1 nanometer, while setting pixels in the SLM to either on or off gives a much coarser pattern. If a pixel on the SLM is projected to a 0.1 µm pixel in the image, a line can only have a width that is an integer number of pixels (n * 0.1 µm where n is an integer). An address grid of 0.1 µm was enough until recently, but the advent of so called optical proximity correction OPC makes a grid of 1 - 5 nanometers desirable. In OPC the size of features in the mask are modified slightly to compensate

for predicted optical image errors when the mask is used. As an example, when a mask with four parallel lines 0.8 μm wide is printed in a modern 4X reduction stepper (a projection printer for semiconductor wafers) they will in a typical case print as lines 0.187, 0.200, 0.200, and 0.187 μm wide although they were intended to have the same width. This can be predicted by simulation of the image formation and the user of the mask may use OPC to compensate in the mask. therefore he wants the first and last line in the mask to be 4 * 0.213 = 0.852 μm instead of 0.800 μm. With an address grid of 0.1 μm he cannot make the correction, but with 5 nm address grid or finer such correction are possible.

The invention is to use the intermediate values between the off-state and on-state to create a fine address grid, e.g. 1/15, 1/25, 1/50, of the size of a pixel. A printed feature consists of pixels in the on state, but along the edge it has pixels set to intermediate values. This is done by driving the pixels with other voltages than the on and off voltages. Since there are several cascaded non-linear effects (the position of the edge versus exposure at the pixels at the boundary, the exposure vs. the deformation, and the deformation vs. the electric field) a non-linear transformation from the input data to the electric field is needed. Furthermore this transformation is calibrated empirically at regular time intervals.

The design of the phase-type SLM

A cloverleaf mirror design as used in prior art is possible to drive to intermediate states between on and off states. However, when the integrated complex amplitude is plotted as a function of deflection, it is seen that it never goes to zero completely but circles around zero, therefore having a

non-zero minimum reflectivity with a varying phase angle. A thorough analysis of an image with some pixels set to intermediate states shows that the position of the edges in the final image are not stable through focus if the integrated phase angle of the edge pixels is not zero. In a preferred embodiment of the invention a new type of pixels with pivoting elements is used. When the elements pivots one end moves toward the light source and the other end away from it thereby keeping the average phase close to zero. Furthermore the cloverleaf design has a problem of built-in stress created during the fabrication. This stress tends to give a partial deformation without an applied electric field. The built-in deformation is not perfectly the same in every pixel since it depends on imperfections during the manufacturing. In the cloverleaf design this difference from pixel to pixel creates a first-order variation of reflectivity. With pixel cells built from pivoting elements the same effect occurs, but gives a second-order effect. Therefore the uniformity is better in the projected image.

Image enhancements.

There is a third advantage with a pivoting design: the cloverleaf does not reach full extinction, but a pivoting cell can more easily be given a geometry that gives full extinction, or even goes through zero and comes back to a small non-zero reflection, but with reversed phase. With better extinction there is greater freedom to print overlapping exposures, designing for a small negative value gives better linearity close to extinction. Printing with a weak exposure, approximately 5%, in the dark areas, but with reversed phase can give an increased edge sharpness of 15 - 30 % and the ability to print smaller features with a given lens. This is an analog to so called attenuating phase-shifting masks that are used in the semiconductor industry. A related method of increasing the edge acuity is

to set the pixels that are inside a feature a lower value and those near the edge a higher value. This gives a new type of image enhancement not possible with current projection of patterns from masks or by the use of projectors following Nelson and Kück. The combination of a non-zero negative amplitude in the background and an increased exposure along the edges need not conflict with the creation of a fine address grid by driving edge pixels to intermediate values, since the effects are additive or at least computable. When the pixels are substantially smaller than the feature to be printed there exists a combination of pixel values that creates all effects simultaneously. To find them requires more computation than the generation of a fine address grid alone, but in some applications of the invention the ability to print smaller features can have a high value that pays for
the extra effort.

In the case of a continuous mirror on an viscoelastic layer there is an inherent balancing of the average phase to zero. Simulations have shown that the driving to intermediate values for fine positioning of feature edges work also for the continuous mirror. The non-linearities are smaller than with micromirrors. But for the method to work well the minimum feature has to be larger than with micromirrors, i.e. have a larger number of addressed pixels per resolved feature element is needed. Consequences are a larger SLM device and that for given pattern the amount of data is larger. Therefore the micromirrors have been chosen in a first and second embodiment.

In the invention a pixel with rotation-symmetrical deformation (at least two-fold symmetry, in a preferred embodiment four-fold symmetry) is

used for two reasons: to give a symmetrical illumination of the pupil of the projection lens and to make the image insensitive to rotations. The latter is important for printing a random logic pattern on a semiconductor wafer. If there is an x-y asymmetry the transistors laid-out along the x axis will have a different delay from those along the y axis and the circuit may malfunction or can only be used at a lower clock-speed.

Preferred embodiments

A first preferred embodiment is a deep-UV pattern generator for photomasks using an SLM of 2048 x 512 micromirrors. The light source is an KrF excimer laser with a pulsed output at 248 nanometers, pulse lengths of approximately 10 ns and a repetition rate of 500 Hz. The SLM has an aluminum surface which reflects more than 90% of the light. The SLM is illuminated by the laser through a beam-scrambling illuminator and the reflected light is directed to the projection lens and further to the photosensitive surface. The incident beam from the illuminator and the exiting beam to the lens are separated by a semitransparent beamsplitter mirror. Preferably the mirror is polarisation-selective and the illuminator uses polarised light, the polarisation direction of which is switched by a quarter-wave plate in front of the SLM. For x and y symmetry at high NA the image must be symmetrically polarised and a second quarter-wave plate between the beamsplitter and the projection lens creates a circularly polarised image. A simpler arrangement when the laser pulse energy allows it is to use a non-polarising beamsplitter. The quarter-wave plate after the second pass through the beamsplitter is still advantageous, since it makes the design of the beam-splitting coating less sensitive. The simplest arrangement of all is to use an oblique incidence at the SLM so that the

beams from the illuminator and to the projection lens are geometrically separated.

The micromirror pixels are 20 x 20 µm and the projection lens has a reduction of 200X, making on pixel on the SLM correspond to 0.1 µm in the image. The lens is a monochromatic DUV lens with an NA of 0.8, giving a point spread function of 0.17 µm FWHM. The minimum lines that can be written with good quality are 0.25 µm.

The workpiece, e.g. a photomask, is moved with an interferometer-controlled stage under the lens and the interferometer logic signals to the laser to produce a flash. Since the flash is only 10 ns the movement of the stage is frozen during the exposure and an image of the SLM is printed, 204.8 x 51.2 µm large. 2 milliseconds later the stage has moved 51.2 µm, a new flash is shot and a new image of the SLM is printed edge to edge with the first one. Between the exposures the data input system has loaded a new image into the SLM, so that a larger pattern is composed of the stitched flashes. When a full column has been written the stage advances in the perpendicular direction and a new row is started. Any size of pattern can be written in way, although the first preferred embodiment typically writes patterns that are 125 x 125 mm To write this size of pattern takes 50 minutes plus the time for movement between consecutive columns.

Each pixel can be controlled to 25 levels (plus zero) thereby interpolating the pixel of 0.1 µm into 25 increments of 4 nanometers each. The data conversion takes the geometrical specification of the pattern and translates it to a map with pixels set to on, off or intermediate reflection. The datapath must supply the SLM with 2048 * 512 * 500 words of data per

second, in practice 524 Mbytes of pixel data per second. In a preferred embodiment the writable area is maximally 230 x 230 mm, giving up to 230 / 0.0512 = 4500 flashes maximum in a column and the column is written in 4500 / 500 = 9 seconds. The amount of pixel data needed in one column is 9 x 524 = 4800 Mb. To reduce the amount of transferred and buffered data a compressed format is used, similar to the one in Sandström at al. 90, but with the difference that a pixel map is compressed instead of segments with a length and a value. A viable alternative is to create a pixel map immediately and use commercially available hardware processors for compression and decompression to reduce the amount of data to be transferred and buffered. . Even with compression the amount of data in a full mask makes it highly impractical to store pre-fractured data on disk, but the pixel data has to be produced when it is used. An array of processors rasterise the image in parallel into the compressed format and transfer the compressed data to an expander circuit feeding the SLM with pixel data. In the preferred embodiment the processors rasterise different parts of the image and buffer the result before transmitting them to the input buffer of the expander circuit.

A second preferred embodiment

In a second preferred embodiment the laser is an ArF excimer laser with 193 nm wavelength and 500 Hz pulse frequency. The SLM has 3072 x 1024 pixels of 20 * 20 μm and the lens has a reduction of 333X giving a projected pixel of 0.06 μm. There are 60 intermediate values and the address grid is 1 nanometer. The point spread function is 0.13 μm and the minimum line 0.2 μm. The data flow is 1572 Mbytes/s and the data in one column 230 mm long is 11.8 Gb.

A third preferred embodiment is identical the second one except that the matrix of pixels is rotated 45 degrees and the pixel grid is 84 μm, giving a projected pixel spacing along x and y of 0.06 μm. The laser is an ArF excimer laser and the lens the reduction of 240. Because of the rotated matrix the density of pixels in the matrix is less and the data volume is half of the previous embodiment but with the same address resolution.

Laser flash to flash variations.

The excimer laser has two unwanted properties, flash-to-flash energy variations of 5% and flash-to-flash time gitter of 100 ns. In the preferred embodiments both are compensated in the same way. A first exposure is made of the entire pattern with 90% power. The actual flash energy and time position for each flash is recorded. A second exposure is made with nominally 10 % exposure and with the analog modulation used to make the second exposure 5 - 15% depending on the actual value of the first one. Likewise a deliberate time offset in the second exposure can compensate for the time gitter of the first one. The second exposure can fully compensate the errors in the first, but will itself give new errors of the same type. Since it is only on average 10% of the total exposure both errors are effectively reduced by a factor of ten. In practice the laser has a time uncertainty that is much larger than 100 ns, since the light pulse comes after a delay from the trigger pulse and this delay varies by a couple of microseconds from one time to another. Within a short time span the delay is more stable. Therefore the delay is measured continuously and the last delay values, suitably filtered, are used to predict the next pulse delay and to position the trigger pulse.

It is possible to make corrections for stage imperfections in the same way, namely if the stage errors are recorded and the stage is driven with a compensating movement in the second exposure. Any placement errors that can be measured can in principle be corrected in this way, partially or fully. It is necessary to have a fast servo to drive the stage to the computed points during the second exposure. In prior art it is known to mount the SLM itself on a stage with small stroke and short response time. Another equally useful scheme is to use a mirror with piezoelectric control in the optical system between the SLM and the image surface, the choice between the two is made from practical considerations.

The second exposure is preferably done with an attenuating filter between the laser and the SLM so that the full dynamic range of the SLM can be used within the range 0 -
15 % of the nominal exposure. With 25 intermediate levels it is possible to adjust the exposure in steps of 15% * 1/25 = 0.6%.

The response varies slightly from pixel to pixel due to manufacturing imperfections and, potentially, also from ageing. The result is an unwanted inhomogeneity in the image. Where image requirements are very high it may be necessary to correct every pixel by multiplication with the pixels inverse responsivity which is stored in a lookup memory. Even better is the application of a polynomial with two, three or more terms for each pixel. This can be done in hardware in the logic that drives the SLM.

In a more complex preferred embodiment several corrections are combined into the second corrective exposure: the flash to flash variation, flash time gitter, and also the known differences in the response between

the pixels. As long as the corrections are small, i.e. a few percent in each they will add approximately linearly, therefore the corrections can be simply added before they are applied to the SLM. The sum is multiplied with the value desired exposure dose in that pixel.

Alternative illumination sources

The excimer laser has a limited pulse repetition frequency (prf) of 500 - 1000 Hz depending on the wavelength and type of the laser. This gives large fields with stitching edges in both x and y. In two other preferred embodiments the SLM is illuminated with a pulsed laser with much higher prf, e.g. a Q-switched upconverted solid state laser, and with a continuous laser source scanned over the surface of the SLM, so that one part of the SLM is reloaded with new data while another part is printed. In both cases the coherence properties of the lasers are different from the excimer laser and a more extensive beam-scrambling and coherence control is needed, e.g. multiple parallel light paths with different pathlengths.

In the preferred embodiment with scanning illumination two issues are resolved: the pulse to pulse variation in time and energy, since the scanning is done under full control preferably using an electrooptic scanner such as acoustooptic or electrooptic, and many continuous laser have less power fluctuation that pulsed lasers. Furthermore the use of continuous lasers give a different selection of wavelengths and continuous lasers are less dangerous to the eye than pulsed lasers. Most important, however, is the possibility of reaching much higher data rates with a matrix with only a few lines since the scanning is non-critical and can be done with 100 kHz

repetition rate or higher. Scanning the illumination beam is also a way of creating a very uniform illumination, which is otherwise difficult.

Edge overlap

Since a two-dimensional field is printed for each flash and the fields are stitched together edge to edge to edge the stitching is very critical. A displacement of only a few nanometers of one field will create pattern errors along that edge that are visible and potentially detrimental to the function of an electronic circuit produced from the mask. An effective way of reducing the unwanted stitching effects is to print the same pattern in several passes but with a displacement of the stitching boundaries between the passes. If the pattern is printed four times the stitching error will occur in four positions, but with only a fourth of the magnitude. In a preferred embodiment of the current invention the ability to create intermediate exposures is used together with an overlap band between the fields. The values are computed during the rasterisation , although it could also be done during the expansion of the compressed data. Edge overlap reduces the stitching errors with much less throughput penalty than multipass printing.

Modified illumination

In the first preferred embodiment the illumination of the SLM is done by an excimer laser and a light scrambler such as a fly-eye lens array to create an illumination that resembles that from a circular self-luminous surface in the pupil plane of the illuminator. In order to increase the resolution when printing with a specific projection system it is possible to use a modified illumination . In the most simple cases pupil filters are introduced in the pupil plane of the illuminator, e.g. with a quadrupole-shaped or annular

transmission area. In a more complex case the same field is printed several times. Several parameters can be made to vary between the exposures, such as focus in the image plane, illumination pattern, data applied to the SLM and pupil filter in the pupil plane of the projection optics. In particular the synchronised variation of the illumination and a pupil filter can give an increased resolution, most notably if the pupil has and a sector-shaped transmitting area and the illumination is aligned so that the non-diffracted light intercepts an absorbing stop near the apex of the sector

Linearisation of the response

For linearisation of the transfer function from data to edge placement here are essentially three ways to go:

– taking the non-linearity into account in the data conversion unit and generating an 8 bit (example) pixel values in the data conversion unit and use DACs with the same resolution to drive the SLM

– to generate digital values with fewer values, e.g. 5 bits or up to 32 values, and translate them to an 8 bit value in a look-up table (LUT) and then feed the 8 bit values to the DACs.

– to use a 5 bit value and semiconductor switches to select a DC voltage that is generated by one or several high-resolution DACs.

In either case it is possible to measure an empirical calibration function such that the response on the plate is linearised, when said function being

applied at respectively the data conversion unit, the LUT or in the DC voltages.

Which linearization scheme to use depends on the data rate, the precision requirements and also on the available circuit technology that may change over time. At the present time the data conversion unit is a bottleneck and therefore it is not a preferred solution to linearise in the data conversion unit, neither to generate 8-bit pixel values. High-speed DACs are expensive and power-hungry and the most appropriate solution is to generate DC voltages and use switches. It is then possible to use even higher resolution than 8 bits.

References:

Nelson 1988: US patent US 5,148,157

Kück 1990: European patent EP 0 610 183

Sandström et al. 1990: European patent EP 0 467 076

What is claimed is

1. an apparatus for printing high precision patterns on a light sensitive surface, such as a microlithographic pattern on a photomasks, a semiconductor wafer, a visual display panel, an optical diffractive device and a precision circuit board, by light projection of a computer-controlled

reflective spatial light modulator composed of a one- or two-dimensional array of pixels, said pattern being described in a digital input format,

comprising

a data conversion unit for converting the digital input format to a pixel map where each pixel can take one of a finite number of pixel values larger than 2,

a data delivery unit for feeding the pixel values to the array of pixels.

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SAMMANDRAG

Föreliggande uppfinning hänför sig till skrivning av mönster med extremt hög precision på ljuskänsliga ytor, såsom fotomasker för halvledaranordningar och skärmar.

Den hänför sig också till direkt skrivning av halvledaranordningsmönster, skärmytor, integrerade optiska organ och elektroniksammankopplingsstrukturer. Vidare kan den ha tillämpningar vid andra typer av precisionsskrivning såsom säkerhetsskrivning.

Mer specifikt avser uppfinningen en anordning för skrivande av hög-precisionsmönster på en ljuskänslig yta med ljusprojicering av en datorstyrd reflekterande spatialljusmodulator bestående av en- eller tvådimensionella grupper av pixlar, där nämnda mönster beskrivs i ett digitalt ingående format. Anordningen omfattar en dataomvandlingsenhet för omvandlande av det digitala ingående informatet till en pixelavbildning, där varje pixel kan inta ett av ett ändligt antal pixelvärden större än 2, och en datalevereringsenhet för matande av pixelvärden till gruppen av pixlar.

Fig 1

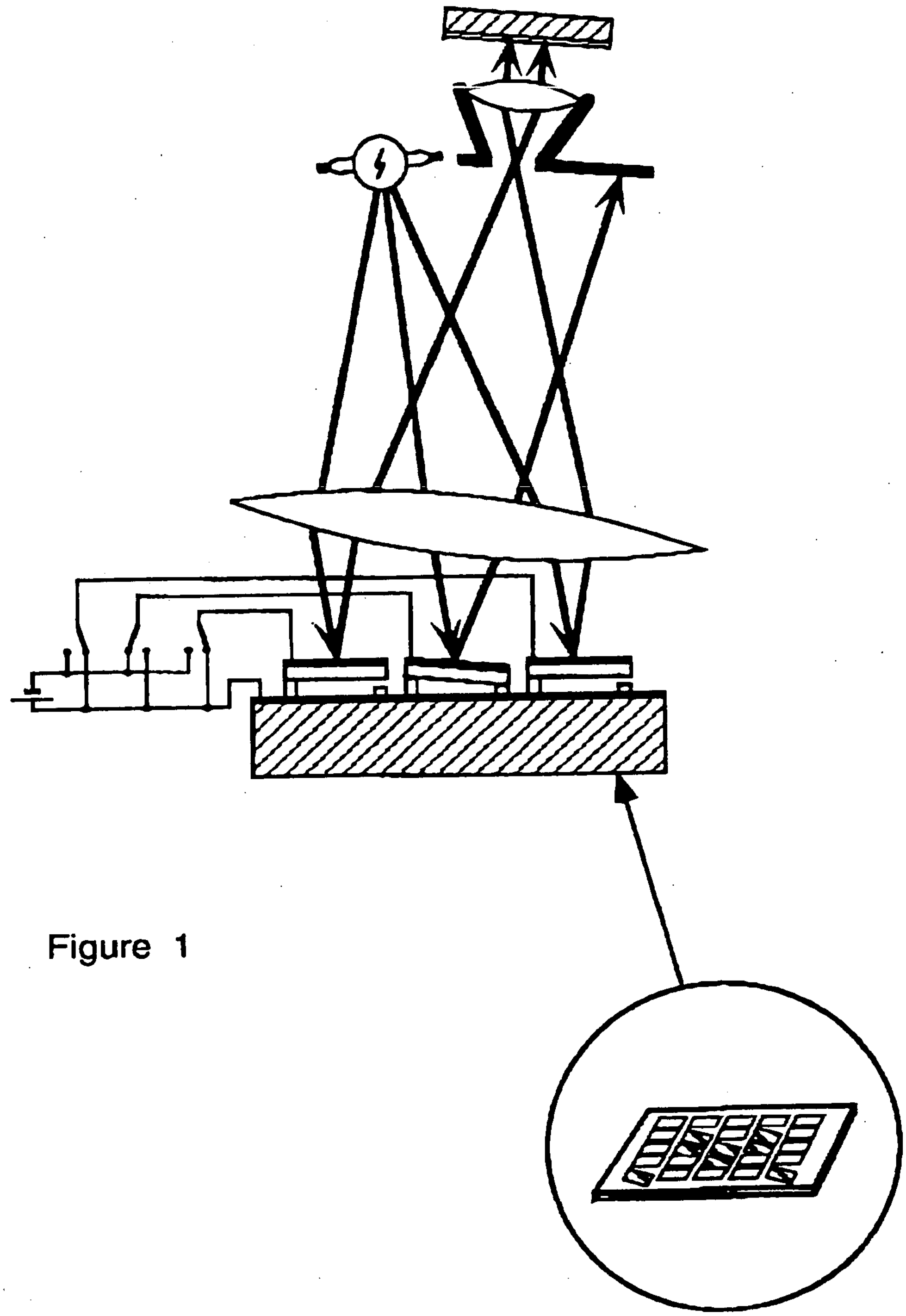

Figure 1

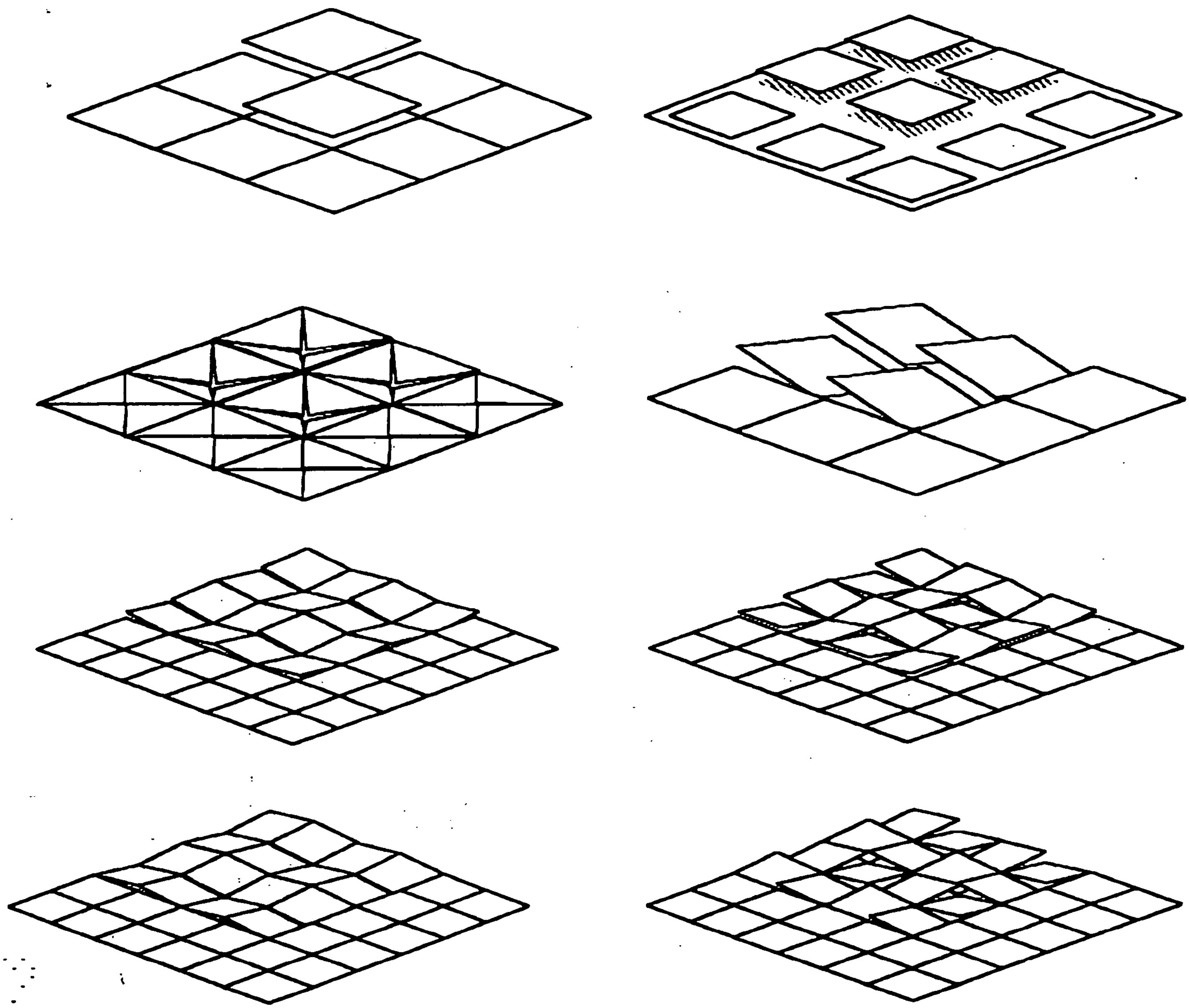

Figure 2

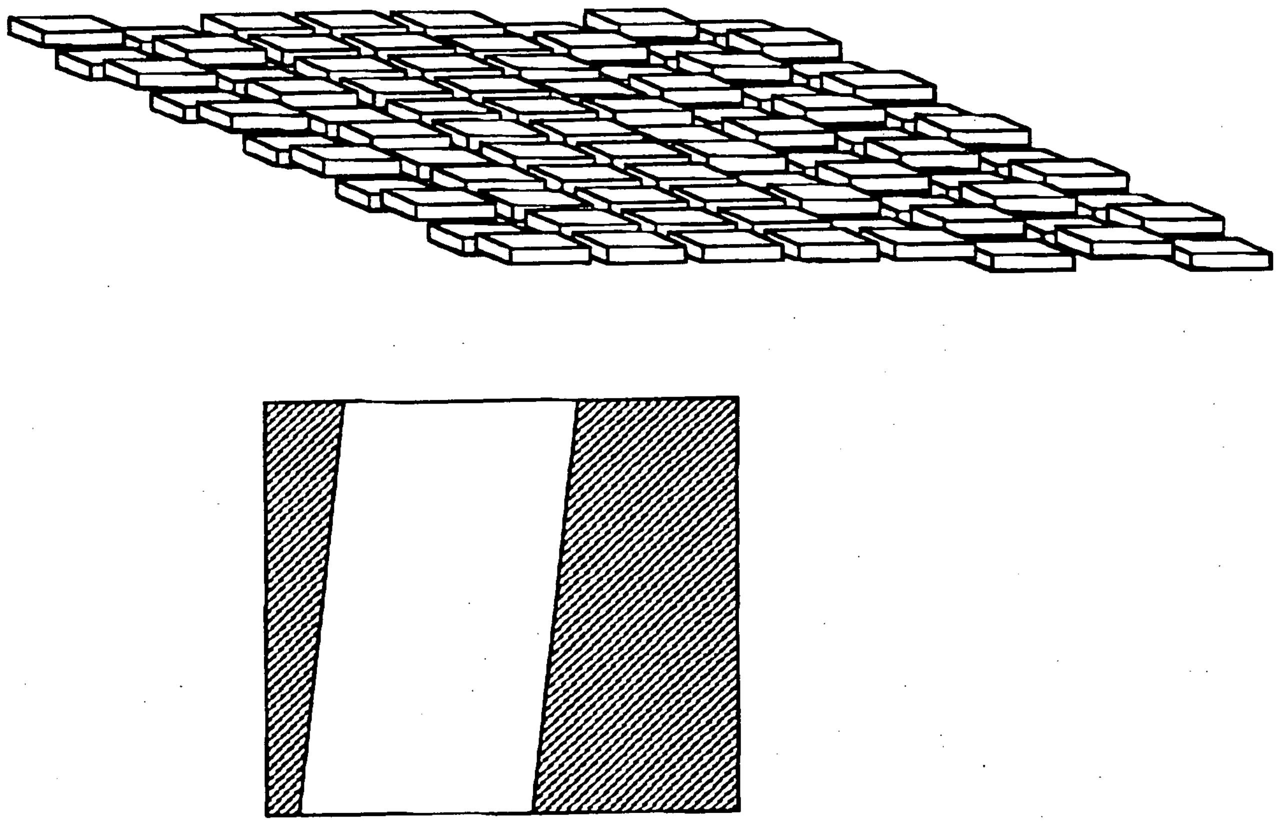

Fig 3